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Menas Kafatos
Chapman University, kafatos@chapman.edu

Andrew G. Michalitsianos

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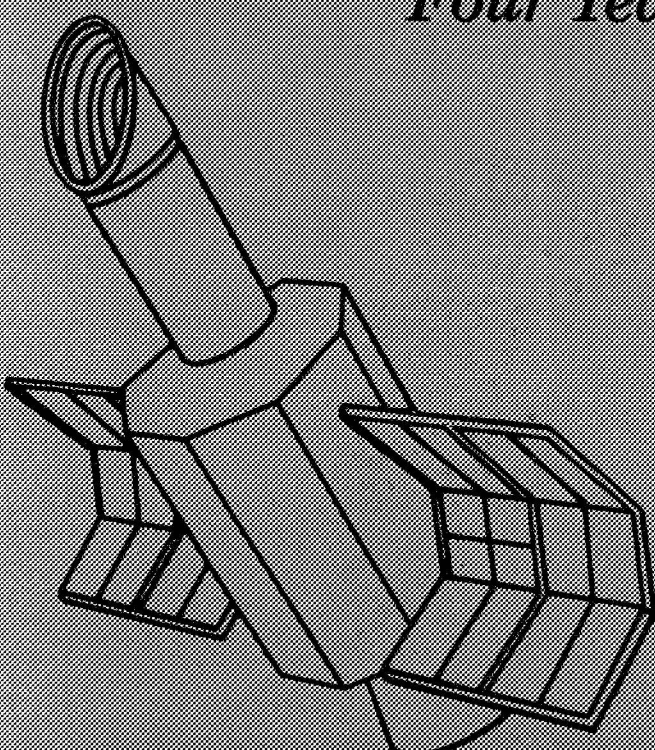

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OBSERVATIONS AND ANALYSIS OF THE R AQUARII JET

Minas Kafatos
and
Andrew G. Michalitsianos
Laboratory for Astronomy and Solar Physics
NASA Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

Ultraviolet, optical and radio observations of the symbiotic star R Aquarii are discussed in the light of the discovery of a bright radio and optical jet from this star. The star is probably a binary with a period of 44 years. The VLA maps of the jet reveal a protruding structure extending $\sim$10 arc sec from the central radio source with a position angle virtually identical to that of the optical jet observed at Lick. We interpret the observations of R Aqr as indicating the existence of an accretion disk around an unseen companion. The hot subdwarf has effective temperature $\lesssim$65,000 K. We believe that the Mira primary and the hot secondary are in orbit around each other with a high eccentricity. At periastron the hot subdwarf accretes at super critical rates and a jet forms. It is difficult to understand how an accretion disk would have eclipsed the Mira in 1928-1935 and 1974-1980. We prefer to interpret the suppression of maximum light in these two periods as due to a distortion of the Mira envelope at periastron by the tidal interaction with the secondary. The jet may help to explain the excitation of the R Aqr nebula. It is possible that R Aqr flared up as a nova$\sim$1000 years ago forming the nebula.

INTRODUCTION

R Aquarii is a symbiotic system which contains a Mira variable having a period of 387 days. The system has long been known to be surrounded by a complex emission nebulosity. Outward motion of this nebulosity was suspected by Hubble (1940 and 1943) and confirmed by Baade (1943, 1944) who estimated an ejection of the nebula about 600 years ago. There is also nebulosity much nearer the star, variable to some extent in both brightness and structure; it tends to be extended north and south of the star, at right angles to the outer arcs. A new feature of this inner nebulosity appeared between 1970 and 1977, in the form of a jet or spike extending approximately 10 arc sec toward position angle 24 degrees. It was observed by Wallerstein and Greenstein (1980) and by Herbig (see Sopka et al. 1982). The same jet has also been observed in radio waves at 6 cm and possibly at 2 cm (Sopka et al. 1982). At 6 cm its intensity is $\sim$ 25% of the primary source at R Aqr itself. Moreover, in a wider field a spatially unresolved source has been detected approximately 3 arcmin from R Aqr close to the axis defined by the jet. The morphology of the jet at 6 cm is strikingly similar to that seen in the near ultraviolet direct plate obtained at the Lick Observatory. On the 1960 Lick plates obtained by Herbig (Sopka et al. 1982) the brightest features of the inner nebulosity are the three knots or condensations A, B, C, and a peculiar, horseshoe-shaped loop opened toward the star and extending about 8" south. The most recent plates were taken on October 18, 1980. Mrs.Janet Mattei has kindly informed us that AAVSO observations show that minimum light occured on October 21, 1980. In the 1980 Lick exposures a bright jet projecting slightly east of north is apparent. It extends about 10" in both the red and ultraviolet plates toward position angle 22^{o} and it is an order of magnitude brighter than any other part of the inner or outer nebulosity. Wallerstein and Greenstein (1980) reported detecting a "spike" of emission nebulosity extending north of Aqr at the time of the deep minimum of September 1977. It is clear that the spike must have appeared between 1970 and 1977. A series of spectrograms taken of the spike at the Coudé focus of the 120-inch telescope reveal a mean spike velocity -71 km s^{-1} (heliocentric) in the mean, while knot B shows a mean velocity of -24 km s^{-1}.

The ultraviolet IUE observations of R Aqr by Michalitsianos, Kafatos and Hobbs (1980) have been re-interpreted in the light of the higher extinction, E_{B-V} = 0.65 (Wallerstein and Greenstein 1980). We find that the size of the inner, high density nebula responsible for the IUE lines and continuum has a radius of $\sim 2.5 \times 10^{14}$ cm and electron density $n_e \sim 5 \times 10^{6}$ cm^{-3}. If a hot subdwarf is responsible for the photo-excitation of this nebula its effective temperature has to be less than 65,000 K to account for the weakness or complete abscence of He II emission and most probably $T_{eff} \lesssim 35{,}000$ K. Its luminosity is 14 $L_{\odot}$ and it is located in the lower part on the H-R diagram occupied by central stars of planetary nebulae.

DISCUSSION

Merrill (1935, 1950) discussed the behavior of R Aqr in 1919 -1949. He finds from the radial velocities of the nebular lines in 1920-1950 that the eccentricity of the orbit is high (e = 0.5). Willson, Garnavich and Mattei (1981) have studied the light of the Mira in the last 100 years and find that the maximum of the Mira was suppressed in the late 20's-early 30's and again in the late 70's. They interpret this effect as an eclipse of the Mira by a cloud. From the duration of the "eclipse" of $\sim$8 years they conclude that the eclipse should have taken place at apoastron in a highly elliptical orbit. They find an orbital period of 44 years. We believe this period but we have difficulty in accepting the simple eclipse interpretation. If the eccentricity of the orbit is high (say e = 0.85, see below) then for a 44 year period and a combined mass of the two stars of 2.5 $M_{\odot}$ we find that the minimum size of the occulting disk or nebula is obtained if the line of sight to the earth is along the major axis of the ellipse and the eclipse takes place at apoastron. This size is $\sim 2\ R_1$ where the index "1" refers to the Mira. This value is similar for other masses of the system stars. What kind of gas (presumably disk) could eclipse a Mira? We find that the luminosity of the disk should be not more than $\sim$1/5 of the Mira luminosity and it should be spatially thick ($h/r \gtrsim \frac{1}{2}$). The disk temperature in the outer regions should then be appreciably less than the effective temperature of the Mira, T_{eff} = 2800 K (Willson 1981). Such cool extended disks are difficult to envisage around a hot subdwarf. Moreover, the IR brightness of such a disk would be in excess of the Mira. We favor an interpretation where the suppression of the light of the Mira occurs near periastron and is due to the distortion of the Mira envelope by the compact secondary. Due to the extended shape of the Mira envelope, we can see further into the Mira atmosphere than normally and, therefore, the Mira appears smaller and less luminous. We emphasize that the radial curves of Merrill (1950) indicate that the timing of the suppression of the Mira light occured much closer to the periastron of 1940.

The extended nebula is still expanding with a velocity of 50 - 100 km s^{-1} (see Hubble 1940, 1943). From the densities of Wallerstein and Greenstein (1980) and using a filling factor of 0.1 for the nebula we find an average electron density in the nebula $\langle n_e \rangle \gtrsim 10^4$ cm^{-3}. The mass of the nebula is $\sim$0.2 $M_\odot$ and its kinetic energy greater than $2x10^{46}$ erg. We note that typical nova light outputs are in the range 10^{44} - 10^{45} erg (Payne-Gaposchkin 1964) while they are $\sim 10^{45}$ for slow novae, RR Tel and RT Ser which may be more closely associated to R Aqr. The nebula radiates more than $5x10^{44}$ erg every year in Balmer, Lyman continuum and lines! The cooling timescale of the nebula is $\sim$ 2 years and one may ask what powers the nebula at least 600 years after the outburst that produced it. A hot star would have to be much brighter than the Mira and would be radiating in excess of the Eddington limit for 1 $M_\odot$. We suspect that the jet may help to power the nebula. Taking a minimum size of the jet of 7", corresponding to a linear size of $\sim 2x10^{16}$ cm, and assuming that it travelled that distance since 1970 we find a jet velocity of 700 km s^{-1}. If the mass of the jet is a few $x10^{-5}$ $M_\odot$-as result of supercritical accretion lasting a few years near periastron-we find a kinetic energy of the jet at present of a few $x10^{44}$ erg. Such jets forming approximately twice a century could deposit enough energy in the last hundreds of years to possibly explain the high excitation state of the nebula.

What is the origin of the jet? We attribute it to a supercritical accretion onto a compact secondary (cf. Bath 1977). We have modelled accretion disks around a 10^9 cm hot subdwarf and we find that the disk would be characterized by drift velocities of $\sim 6.5\,\alpha$ km s^{-1}, where α is the usual viscocity parameter (Shakura and Sunyaev 1973). For a reasonable value $\alpha \sim 0.1$ the disk would last about 10 years. From Willson (1981) we find that the radius of the Mira $R_1 \sim$ 300 $R_\odot$, its mass $M_1 \sim 1.5$ $M_\odot$. It follows that the Mira fails to fill its Roche lobe by at least a factor of 5. The possibility remains, however, that the orbit is higly elliptical and the Mira fills its Roche lobe only at periastron, while during the rest of the orbit, the secondary accretes material from the cool stellar wind expelled from the Mira. The presence of the jet suggests the existence of a well developed accretion disk if R Aqr is similar to other stellar objects with jets such as SS 433 (cf. Margon 1982). The compact star would be accreting material from the disk at super-Eddington values if the mass accretion rate is larger than $4.3x10^{-5}$ $M_\odot$ yr^{-1}. Such large rates would occur if the orbit is highly elliptical ($e \gtrsim 0.84$) and the periastron is $\sim$ 1 to 2 times the radius of the Mira. The appearance of the jet $\sim$ 44 years after the outburst of 1928-1935 would then be indeed tied to the orbit of the two stars. Such a disk and jet would make an excellent Space Telescope target because of the proximity of R Aqr. At B wavelengths the disk would be about 3 magn brighter than the Mira at minimum light.

The nebula must have been ejected about 550 - 1100 years ago for a distance of 200 pc and a radius of 1'. We find that the only recorded nova outburst in historical times from the Chinese and Japanese records was that of 930 A.D. (Hsi Tsê-tsung 1958; Pskovskii 1972). The outburst is described as "guest star entering Yũlin". Yũlin is a faint ancient Chinese asterism in Aquarius. The term "entering" could mean "at the edge of" (Clark, private communication). The approximate coordinates of the guest star of 930 A.D. are R.A. $\sim$ 23 h, Dec $\sim$ -20°, within 10° of R Aqr and near the edge of Yũlin. The probability of finding a random nova inside Yũlin-and near R Aqr-is extremely small (R Aqr is 70° below the galactic plane), less than 0.02 in the last 1000 years. It is, therefore, highly probable that the 930 outburst is associated with the R Aqr outburst that produced the extended nebula. If this is correct, it would be the first nova-like outburst that is tied to the Chinese records.

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